Science Requirements Flow-Down Tables for the Next Generation UVOIR Space Telescope

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Version: 01-November-2013

Abstract

As part of a NASA center study on the design and technology requirements for a next generation, large aperture space telescope (hereafter referred to as ATLAST), an ad hoc science team developed updated science requirements for such a facility. These requirements flow from a series of high-level science questions that are driving the frontier of knowledge in astrophysics and exoplanet research. The requirements are summarized in a series of tables and are meant to be a starting point to define a working range of observatory performance requirements that will enable more detailed engineering and technology development requirements to be established over the course of the next several years leading, ultimately, to a compelling and viable flight mission concept proposal that would be considered by the 2020 Astronomy & Astrophysics Decadal Review. The current science requirements contained here are not meant to be comprehensive but imply a sufficiently wide range in angular and spectral resolution and in wavelength and sensitivity that it is easy to envision that a facility with such capabilities would also enable many as yet unimagined scientific investigations.

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Executive Summary of Telescope Properties:

The team identified 13 high-level science questions and explored the implementation implications for each. Some were explored in greater detail than others. Some open issues for some astronomical measurement specifics remain and additional effort will be needed to generate those requirements. The 13 science questions explored in this work are:

1. Are there habitable planets around solar-type stars?
2. Do any of these planets exhibit evidence for biological activity?
3. How diverse are planetary systems?
4. What are the star formation histories of local galaxies?
5. What are the kinematic properties of Dark Matter?
6. What is the history of galaxy assembly in the post-reionization era?
7. What is the contribution of faint galaxies to reionization?
8. How do the first galaxies form stars and metals?
9. What are the flows of matter and energy in the circumgalactic medium?
10. What controls the mass-energy-chemical cycles within galaxies
11. How do black holes grow, radiate, and influence their surroundings?
12. What are the astrophysical processes that control the evolution of massive stars?
13. How do circumstellar disks evolve and form planetary systems?

Table 1 below summarizes the common key performance requirements that were identified as part of this current science requirements exercise. The science reference column points to the specific science case (see first column in each science flowdown table) where a given telescope performance requirement is identified.

Table 1. Summary of Telescope Design Parameter Requirements

Telescope Parameter	Consensus Requirement	Science Drivers (Question #)
Primary Mirror Aperture	8-meters (min), 14-meters (nominal)	All
Vis/NIR Coverage	300 nm – 2.5 microns (background limited)	1,2,4,5,6,7,8,11
UV Coverage	912 Å – 3000 Å	2,6,9,10,11,12,13
Mid-IR Coverage	Sensitivity up to 8 microns (but with non-cryogenic optics)	3,4,6,8,12,13
Vis/NIR Image Quality	Diffraction-limited performance at 500 nm (~9 mas for 14-meter aperture).	1,2,4,5,6,7,8,11
UV Image Quality	Not worse than 0.10 arcsec at 1500 Å	12,13
Wavefront Error / Stability for General Astrophysics	~35 nm WFE, 1.3 – 1.6 mas pointing stability	4 - 13
Wavefront Error / Stability for Exoplanet Imaging	0.01 – 0.1 nm WFE after active correction in starlight suppression instrument	1,2,3

Table 2 shows the implied requirements for science instrument performance capabilities. The format is similar to that in Table 1.

Table 2. Summary of Science Instrument Capabilities

Science Instrument Parameter	Consensus Requirement	Science Drivers (Question #)
Starlight Suppression System	10^{-11} suppression to IWA of ~40 mas with internal active wavefront sensors and control (may be used in conjunction with or in lieu of an external starshade)	1,2,3
Exoplanet Spectrograph	IFU design with R = 70, 500; FOV ~10 arcsec; 0.3 – 2.5 microns	1,2,3
Exoplanet Imager	IFU design with UV and Vis channel. FOV ~10 arcsec.	1,2,3
UV Spectrograph	912 – 2500 Å, multiple modes covering R = 20,000 – 300,000 (echelle?), FOV 1 – 2 arcminutes, with MOS capability	6,9,10,11,12,13
UV Imager	912 – 3000 Å, FOV 1 – 2 arcminutes	10,12,13
NIR/Vis Imager	FOV 4 – 8 arcminutes, Nyquist sampled at 500 nm, 0.3 – 2 microns	4,5,6,7
NIR Spectrograph	FOV 3 – 4 arcminutes, 0.6 – 2.5 microns, R=100 (Grism), 500, 2000	6,7,11
MIR Imager/Spectrograph	FOV 3 – 4 arcminutes, 3 – 8 microns, R=5, R = 500	6,12,13

The specific requirements for each of the 13 science questions are presented in Tables 3 – 7. We may eventually add a short summary of the science case prior to each table to set the stage but for now this version of the document jumps right to the specific requirements.

Table 3. Science Requirements for Exoplanet and Planetary System Characterization

Science Question	Science Requirements	Measurements Needed	Example of Possible Design and Implementation
SQ1: Are there habitable planets around Solar type stars?	Directly detect at least 10 Earth-like Planets in HZ with 95% confidence (assuming $\eta_{EARTH} = 0.1$ and exozodiacal dust levels are <10 x Solar System level).	High contrast (ΔMag ~ 27 mag if done in visible band) SNR=10 broadband (R=5) imaging with IWA ~ 40 mas for ~ 100 target stars. Habitability signatures: thick atmosphere (Raleigh scattering), water absorption features, orbit within habitable zone (HZ).	Aperture requirement: 8 to 14 meter aperture to achieve sample size (~100 - 300 stars) and to get the desired SNR spectra in <500 ksec for most distant (~25 pc) exoplanets in the sample. Stable 10^{-10} starlight suppression on detector at IWA is the minimum requirement. Suppression factor of ~ 10^{-11} is needed for detecting the required number of Earth-size planets in the HZ around solar type stars. 0.1 nm *RMS* WFE stability ~1.3 to 1.6 mas pointing stability. 10 mas RMS pointing stability after fine steering mirror. IFS with sensitivity from 0.3 to 2.4 μm, with broadband imaging and two spectroscopic modes (R=100, R=500). >50x improvement over HST/COS. Wavelength coverage to 1216 Å.
SQ2: Do any of these planets exhibit evidence for biological activity?	Detect biosignatures in the spectra of Earth-like HZ planets (e.g., molecular oxygen band at 760 nm) Assess photochemical effects and constrain atmospheric models for exoplanets.	High contrast (ΔMag > 27 mag) SNR=10 low-resolution (R=100-500) spectroscopy with an IWA ~ 40 mas. Exposure times <500 ksec. Some key biosignatures: non-equilibrium ratio of molecular oxygen and methane in same spectrum. *UV spectra of host stars (M through F stars to 50 pc) needed to measure input spectra for planet atmosphere photochemical models.*	
SQ3: How diverse are planetary systems?	Characterize a sample of at least 100 exoplanet systems with multiple planets. Sample should be large enough to have 10 systems in each of 10 categories of parent stars (mass & metallicity class, age, etc.). Here, characterize means to determine the planetary system architecture: planet masses, mean densities, atmospheric compositions, orbital parameters, host star properties, and orbital parameters of the planets, and the presence of smaller planetesimal belts	Precision radial velocities (< 10 cm/s from ground) or precise relative astrometry (<0.1 micro-arcsec) over at least a five-year baseline. Direct optical/NIR spectroscopy of planets larger than Earth-size between ~1 AU and ~ 30 AU from their parent stars (within 25 pc). High contrast (ΔMag > 26 mag at IWA, ΔMag > 30 mag at OWA) SNR = 10 low-resolution (R = 100 - 500) spectroscopy with an IWA < 40 mas and OWA > 1.2 arcsec. Characterize methane, CO, H_2O, and CO_2 (and other atomic species) absorption features in planetary atmospheres to better	TBD: The design constraints for this particular science call for a constraint on the outer working angle (OWA) for spectroscopy of planets beyond the ice lines. Also need better contrast at OWA to do direct spectroscopy of Neptune-analogs. Contrast at IWA in column to the left assumes a super-Earth with R = 1.4 R_earth; contrast at OWA assumes a Neptune around the Sun. These limiting contrast values are WAGs; need to be considered more carefully. Goal of 5 μm for spectral range for more extensive characterization of atmospheres, if possible without compromising shorter wavelength

	indicated by debris dust. Study the properties of "escaping" atmospheres of close-in (i.e., hot) exoplanets in UV. Perform more detailed transit observations of TESS super-Earth and Earth-like planet candidates in the optical and NIR.	constrain elemental abundance ratios. High sensitivity (≥1 ppm) and low (R≤100) to medium (R≤3000) resolution absorption line spectroscopy from 1216 Å to 3 microns.	performance. High-speed spectrophotometer that can work at high light levels (for transit spectroscopy applications).

Comments:

Wes Traub: AFTA microlensing – planetary system demography from ice line outward. AFTA coronagraph – imaging of planetary systems out to 20-30 pc – [0.2"] also look at bright debris disks in the asteroidal and Kuiper zone. 0.2" + 20-30 pc gets to 4-6 au….So this is ice line stuff. Perhaps 200 stars will be studied in this way….a reasonable NBT goal would be to repeat the sample with ~one-fifth the IWA, looking now to 1AU and towards rocky planets…implies 12m telescope. AFTA provides not just detection but colors and spectra.

Marshall Perrin: AFTA design is moving towards assuming active real time wavefront control driven by low-order wavefront sensor in closed loop, rather than requiring absolute stability at all relevant timescales. Also final achieved contrast will be the combination of both the optically achieved contrast and gains possible via post-processing of differential imaging data (PSF subtraction, IFS multispectral analyses, etc.). How much gain will be possible for AFTA via PSF subtraction in the 1e-8 to 1e-10 regime is still TBD, will be an active funded area of study over the next few years for AFTA with likely direct application to ATLAST. As mentioned before, how to achieve this may or may not have system-level implications for ability to roll the observatory, or field of regard for accessing PSF reference targets close in time to science targets.

Aki Roberge: There would be some very interesting things to be learned about planetary magnetic fields if UV auroral emission lines could be detected in direct or combined-light spectra.

Bill Sparks: Polarization studies of exoplanets could be interesting. No specific observational constraints were provided, however.

Table 4. Science Requirements for Galaxy and Star Formation History Reconstruction

Science Question	Science Requirements	Measurements Needed	Example of Possible Design and Implementation
SQ4: What are the star formation histories of local galaxies?	Determine the ages and metallicities of resolved stellar populations over a broad range of galactic environments. Accuracy requirements: age bins ~1 Gyr over lifetime of galaxy; metallicity bins of ~0.2 dex over full range of abundances.	Color-magnitude diagrams using broadband imaging (SNR=5) for individual solar analog stars (absolute V mag ~ 5) in spiral, lenticular, and elliptical galaxies for >50 galaxies within 10 Mpc. Imaging must be done in at least two passbands, with bluer band below 0.6 μm wavelength.	1.14-meter primary (8 meter minimum) aperture to observe nearest giant elliptical galaxy and get SNR in 2 passbands in a total exposure <400 ksec. 2. WFE: Diffraction limited at 0.5 μm; 3. ~1.3 to 1.6 mas pointing stability; 4. Symmetric PSF highly desirable **VIS/NIR wide-field (4 - 8 arcmin FOV) imager** at TMA focus for simultaneous photometry of >10,000 stars. ATLAST can probe stars below the main sequence turn off. GSMTs will only be able to study more evolved (giant branch) stars. ATLAST will also probe visible passbands at high resolution, which provide better constraints on ages.
SQ5: What are the kinematic properties of Dark Matter?	Determine the mean mass density profile of high M/L dwarf Spheroidal Galaxies in Local Group.	Proper motions of ~200 stars per galaxy with accuracies ~20 μas/yr at 50 kpc (yielding required transverse velocity accuracy of 5 km/sec). Augment with stellar radial velocities from ground.	1. Aperture diameter: ≥8 m to achieve the angular resolution to enable stellar centroids to be determined to 0.1 mas. Focal plane metrology must be maintained to enable 0.005 pixel centroid accuracy over a 5-year baseline. 2. WFE: Diffraction limited at 0.5 μm; 3. ~1.3 to 1.6 mas pointing stability; PSF ellipticity < 0.30. VIS/NIR wide-field (5 - 8 arcmin FOV) imager at TMA focus. Need wide-FOV to ensure sufficient number of background astrometric references (e.g., galaxies and QSO).

Table 4 continued. Galaxy and Star Formation History Reconstruction

Science Question	Science Requirements	Measurements Needed	Example of Possible Design and Implementation
SQ6: What is the history of galaxy assembly in the post-reionization era?	Trace the evolution of spatially-resolved chemical enrichment, star-formation on sub-kpc scales for galaxies in gas and stars at z<6	Measure spatially-resolved star-formation rates, gas-phase metallicities, and stellar metallicities in galaxies using diagnostic emission lines such as Lyα, [O II] 3727, Hβ, [O III], Hα, and [N II] to z~6 and optical stellar absorption lines such as Mgb to z~2.5. Measure rest-frame UV spectral tracers of massive stars and nebular gas, to probe metallicities, stellar winds and feedback, including emission lines [OVI] 1035, [CIV] 1550, C[III]1902, HeII 1640, and Si[III] 1882, ideally from z<1 to z >6.	Low-resolution NIR/optical grism (R~100) over wide FOV (>2'x2') for surveys of emission-line objects. Multi-object NIR moderate resolution spectrograph/IFU (IFU >2"x2" FOV); Requires R > ~1000 to resolve N[II] /Hα ratios, stellar absorption features, velocity structures at 100 km/s (Multi-object?) UV/optical spectrograph with R >~3000 to resolve doublets for gas ionization parameters, ~50 km/s velocity structures. Rest-frame UV lines require 1000-3000 AA sensitivity for z<1 galaxies. Spatial resolutions <0.05" required to probe SF, metallicity gradients, given compact sizes (~0.1-1.") of distant galaxies. Moderate optical/IR spectral resolution (R~1000) IFU is sufficient for most diagnostics; low-resolution grism useful for surveys (GMT/TMT will have high res. capabilities)
	Trace galaxy assembly at low-mass, low-surface-brightness, high spatial resolution to z~3, e.g. dwarfs, bulges and outer halos Determine galaxy structures, dust and stellar-mass maps at low surface-brightness, high spatial resolution (~100-300 pc).	Deep rest-frame UV/optical/IR imaging for detection, photometric redshifts, rest-frame optical luminosities/colors, UV SFRs, stellar mass (M_B >=-15 at z~3). Deep, high-spatial resolution rest-frame optical/NIR imaging to resolve compact structures, detect outer halos of distant galaxies (200 pc ~ 0.025" at z~3).	Broad-band 0.3-2+ micron imaging down to >31 AB mag 5-sigma, with stable photometric calibration and PSF, <0.05" spatial resolution, with efficient mosaicking/wide-field (>2'x2') FOV. [Deep 2-5+ micron imaging useful for photo-z, and crucial for reliable stellar mass estimates for z>3 galaxies; double check sensitivities v. ground]

Table 4 continued. Galaxy and Star Formation History Reconstruction

Science Question	Science Requirements	Measurements Needed	Example of Possible Design and Implementation
SQ7: What is the contribution of faint galaxies to reionization?	Determine the space density of intrinsically low-luminosity galaxies as a function of redshift over the range 6 < z < 8+	Deep rest-frame UV imaging to directly count the intrinsically faint galaxies ($M_{UV} > -18$) responsible for reionization at z~6-8+; this requires 5 sigma depths >32-33 AB mag at 1-2+ microns; (possible with blank deep fields or lensing) Measure the fraction of UV-ionizing photons that escape from galaxies; impossible to directly measure at reionization b/c of IGM, but can infer from z~3-6 galaxies; rest-frame UV imaging (observed U/B) to surface brightness < 28-29 AB mag/sq arcsec	Very deep broad-band 0.3-2.5 micron imaging down to ~33 AB mag 5-sigma, with stable photometric calibration (especially 1-5 microns), with efficient mosaicking/wide-field (>2'x2') FOV. (~10 hour deep fields or strong lensing fields) Needed depths of observed optical imaging not possible with JWST or with ground-based 30m
SQ8: How do the first galaxies form stars and metals?	Spectroscopically confirm and directly trace massive star-formation, chemical evolution of galaxies before and during reionization (6< z < 10+)	Measure rest-frame UV lines (Ly-alpha, CIV1549, HeII1640, CIII1909, SiIII 1883, 1892, MgII2800) out to z~10-12 to probe metallicity/ nucleosynthesis in early galaxies. Lyα likely to be undetectable at z>7 b/c of IGM absorption. Deep surveys for strong rest-optical line emitters (Hβ, [O III], Hα) at 3 < z < 10; Get redshifts, global star-formation and emission line ratios. These objects are expected to be very high EW (~1000 AA). At z>6, only strongly lensed objects (detected by WFIRST) would be detected.	NIR 1-2.5 micron medium resolution (R~1000) multi-object spectrograph; galaxies are small (<0.5 kpc or 0.3") and faint so IFU would have limited usefulness at z>6; Fainter lines (EW CIII1909 ~5-15 AA) require R~1000 at 1-2.5 microns and 5-sigma sensitivities ~25-28 H AB mag. Deep low-resolution 2-5 micron grism (R~100; 5 sigma at ~1e-17 ergs/s/cm2). Blind surveys would need 2'x2' FOV; Complete spectral coverage of this wavelength range impossible from ground. Should be better than JWST at 1-2.5 microns; post-JWST, ground-based 30m 1-5+ micron spectroscopy will be challenging because of OH lines/limited atmospheric windows.

Comments:

Dan Stark: I've considered the feasibility of three cases below. Here's a brief summary:

(1) The 6-8um sensitivity is not sufficient for detecting [OIII] / H-alpha at z>10.
(2) The 3-5um sensitivity with R=10,000 is good enough for detecting [OIII] / H-alpha in bright lensed galaxies at 6<z<10.
(3) The 1-2um sensitivity with R=10,000 is very well-suited to characterising a large number of UV metal lines in lensed galaxies at z>6. The flux limits are even sufficient for detecting unlensed z~7 objects as faint as H~28 (1 mag below L*).
(4) Perhaps the most feasible path toward z>10 spec. confirmation is CIII]. The K-band sensitivity is good enough to detect EW=13 A (rest-frame) CIII] in z=12 lensed galaxies with K=25.5. It's not clear to me that this will be feasible from the ground. I imagine that the best spectroscopic targets at z>7 will be bright, lensed galaxies discovered in surveys like WFIRST. Unfortunately these will most likely emerge after JWST. So a telescope with some of the capabilities in the chart you've sent would be tremendously valuable and very complementary to GMT/TMT. Details of calculations follow.

1. H-alpha / [OIII] at z>10

Assume galaxy at z=12. H-alpha at 8.5 um, [OIII] at 6.5 um. Both of which are not observable with GMT. Require line flux of 4.7e-15 cgs or 4.7e-16 cgs for detection in 10ks with R= 100 or R=10,000. For the most optimistic situation, consider large EW lines in bright, lensed galaxies. The brightest z=10 galaxies are H~25.5. Assume something like Euclid/WFIRST can find a large population of similarly bright, lensed galaxies at 10<z<15. For a rest-frame EW = 1000 A (as per Smit et al. 2013) and AB=25.5 galaxy at 8.5 um (assuming flat f_nu spectrum, i.e. no Balmer Break), we would expect line fluxes of 1.3e-17 cgs for H-alpha, and 2.2e-17 cgs for [OIII]. If there is a Balmer Break of ~0.5 mag, then [OIII] could get up to 3.4e-17 erg/cm2/s.

So we would need to get between 13-36 times deeper than the 10 ks sensitivity limit for R=10,000. Unless we can find lensed galaxies in the ~23 mag regime at z>10 (not out of the question), I'd think this would be a prohibitive time investment. The same goes for an R=5 setup. The 10-sigma t=10 ks sensitivity of AB=19.32 (6um) and AB=17.77 (8um) is not going to be that useful for even most bright lensed galaxies at z>10.

2. H-alpha / [OIII] at 6<z<10

Similar as above except lines are in the 3-5 um regime. GMT wins out at R~5 in L and M-band, so consider R=10,000 spectroscopy. Here the flux limit is 1.2e-17 (L-band), 4.7e-17 (M-band), and 7.6e-17 (5um).Again adopt 1000A rest-frame EWs. At z~6-7, we're already finding lensed galaxies as bright as AB~23.9-24.5. Assuming flat f_nu (no Balmer Break), we get line fluxes of ~1.5e-16 cgs for [OIII] emission at ~4um in a z=7 AB~23.9

galaxy. H-alpha (with EW=1000 rest-frame) is ~7e-17 cgs at 5 um for the same galaxy. Both of these should be detectable in the t=10 ks exposure. Should be feasible to detect the AB~24.5 galaxies as well. And of course there could be a small Balmer break, which would result in slightly larger line fluxes for the same EW.

So it's clear that this would provide a unique and critical capability in the post JWST era. I'm assuming these sensitivities are better than what NIRSPEC will be able to do?

3. UV metal lines at 6<z<13

Assume C[III]1909 rest-frame EW = 5-13 A. O[III]1661,1667 EW of ~2-3 A. The C[III] line shifts from the J-band to K-band over this redshift range. For the R=10,000 mode, the chart predicts line flux sensitivities of 6e-20 (J-band) to 2e-19 (K-band) for a t=10 ks exposure. For bright lensed galaxies (AB~23.9), we expect line fluxes in the range 0.6-1.5e-17 cgs for C[III], and roughly 30% of that for O[III]. These would be trivial to detect. One could easily detect fainter UV lines (Si III 1883, 1892, He II) and put limits on N[III]1759, NIV which would open up some interesting relative chemical abundance measurements. Importantly, one could detect CIII] with EW = 13 A in z=7 objects as faint as H~28. This is over 1 mag fainter than L* at z=7, so this would enable spectroscopy/redshift confirmation for many unlensed z=7 galaxies.

Mike Shull: Imaging of stellar populations over wide field. Infer SFHistory from hot gas in halos and also the amount of energy which stars pump into the halos. At low redshift, look at emission lines in the UV, equivalent to the [CII] and [NII] lines in the infrared. The UV lines include [CIV] 1550 and [OVI] 1035 doublets.

Richard Ellis: Metal gradients in 1<z<6 galaxies is a key (and new) measurement that traces two phases of galaxy assembly (i) the interaction between inflows of pristine cold gas and outflows of enriched gas and (ii) minor mergers which build up the outer stellar layers.

Daniel Stern: I'm not convinced that getting detailed information on the kinematics of galaxies within galaxy clusters is the most efficacious way to address the connections between dark and luminous matter. Other approaches include: (i) a la Bullet cluster, compare the locations and velocities of galaxies in merging clusters to the location of their dark matter (from weak lensing) and IGM (from X-rays or SZ); (ii) ala CLASH, get very detailed weak and strong lensing constraints on a large sample of galaxy clusters to study substructure in the dark matter distribution.

Table 5. Science Flowdown Requirements for IGM/ISM Characterization

Science Question	Science Requirements	Measurements Needed	Example of Possible Design and Implementation
SQ9: What are the flows of matter and energy in the circumgalactic medium?	Map, at high spatial sampling, the properties and kinematics of the intergalactic and circumgalactic medium, over contiguous regions of the sky, on scales up to ~10 Mpc. Detailed study of the environs of the nearest galaxies to map out their CGM. Watch metals cycle in and out of galaxies.	SNR=20 high resolution (R=20-40,000) UV spectroscopy of quasars down to FUV mag = 22-23. Observe >10 QSOs behind every galaxy out to 10 Mpc to weigh CGM. Use 1032/1038 Å OVI doublet and other rest-FUV ions.	High efficiency UV detectors with at least an 8 m primary aperture to survey wide areas in less than 2 weeks of time. UV coatings that support sensitivity all the way to 900 Å, to access O VI and Lyman series in the nearby Universe.
SQ10: What controls the mass-energy-chemical cycles within galaxies?	Map inflows and outflows of halo and circumgalactic gas into and out of the disks of galaxies. Trace galactic superwinds to their origin points within galaxies.	Measure metallicity and kinematics of outflowing and inflowing gas to trace the gas flows that fuel star formation. Observe spectral lines of, e.g. CIV 1550 and OVI 1032 from 0.05<z<1.5. SNR = 20 or more. Use stellar clusters driving winds as background sources to study those winds in absorption. Critical to access rest-frame UV lines in the local Universe.	Ultraviolet 2D spectroscopy (IFS) of nearby galaxies and multi object spectroscopy (MOS) to study filaments and structures. This will require FOV of 1-2 arcminutes and ~0.5 to 1 arcsec angular resolution at 1200-1500 A. >50 km/s velocity resolution, or R > 6000. FOV: several arcmin, to efficiently cover extended nearby galaxies (e.g. M51, M82) with IFU spectrograph and MOS instrument. Sensitivity ~10 photons cm^{-2} s^{-1} sr^{-1}

Comments:

Mike Shull: Hot gas is virialized in halo – stars repopulate halo with winds driven by star formation and supernovae. Gas cools radiatively while still ionized and then goes into atomic and molecular phases, cycle repeats. Study rest-frame UV emission from z=0 to 1.5. Going into the infrared provide more spectral bands – H2, PAHs, fine structure lines, etc., for a more complete study of the mass-energy-chemical cycle. His science frontier panel investigated these issues out to z~0.1, or ~400MPc. Big project is to study qso's in absorption through galaxy halos…question is how large a telescope is needed depends on quasar luminosity function…8 m gets to 21-22 mag, 16 m might reach 23-24 (very sensitive to desired S/N, obviously). Hubble is making good progress at z~0.1-0.5

[Tumlinson, Tripp, Heckman large programs]. Keck, VLTI from z~1.3-to-5 [Steidel, Simcoe]. HST is not sensitive to fill in the z ~ 1 – 1.5 gap, and has no UV IFU / MOS capability.

Table 6. Science Flowdown Requirements for *Studies of the Physics of the Cosmos*

Science Question	Science Requirements	Measurements Needed	Example of Possible Design and Implementation
SQ11: How do black holes grow, radiate, and influence their surroundings?	Measure AGN / SMBH masses as a function of cosmic time and environment.	Velocity dispersion measurements in central 100 pc regions of galaxies. Will need to use prominent lines (H-alpha, OIII, OII, Ly-alpha) to cover full redshift range from $0 < z \leq 7$.	R=1000-2000 UVIS spectrograph. FOV for this application is 1 arcsecond. Single aperture or long-slit should suffice but IFU also OK.

Comments:

Marc Postman: Black hole mass determination at high-z might be doable using extreme AO system on large ground-based telescopes. Need to think about higher order science that can be done from space.

Richard Ellis: Beyond z>8 there is only one diagnostic line, lyman alpha, in the region shortward of 2.5um. We know we can go to very high z…want to measure metallicity, e.g., from OII plus OIII. UDF12 determined that reionization by galaxies requires observing a faint population 4 magnitudes deeper than can be seen by HST. So probing to 0.01 L* is simply not deep enough. Note also many of these faint objects are truly tiny so exquisite resolution is essential (better than JWST).

Table 7. Science Flowdown Requirements for *Studies of the Life Cycle of Stars in the Milky Way and Nearby Galaxies*

Science Question	Science Requirements	Measurements Needed	Example of Possible Design and Implementation
SQ12: What are the astrophysical processes that control the evolution of massive stars?	Measure the low-end of the metallicity distribution in massive (>5 solar masses) stars.	Vis/UV color-magnitude measurements of star forming regions with spatial resolutions of 0.1 pc (comparable to local studies of 30 Dor). Need SNR≥10 UV photometry High spectral resolution (R≥100,000) UV data for numerous individual OB stars.	8 to 14 meter UV telescope. System must have sensitivity down to 912 Å. Imaging quality: diffraction-limited at 0.5µm or shorter. *This science case appears to require 0.1" angular resolution in UV. How hard is this if mirror diffraction limited at 500 nm? Implications for segment phasing stability?* Instruments: • UV spectrograph (with R>100,000 for 3 km/s resolution (R > 300,000 for 1 km/s resolution). Longslit capability needed for spatially resolved spectroscopy. • UV/Vis imager with few arcmin FOV. Nyquist sampling required. Infrared wavelength coverage out to 10um to cover the ice and PAH features in the 5-8um region. Spatial resolution ~0.1" longward of 5um to resolve central ~10" diameter of protoplanetary disks in nearest star forming regions. Imaging and low-resolution (R~100-to-200) spectroscopy, 2-10um. For spectroscopy, 10-sigma limits ~0.2mJy at 5um, ~5mJy at 10um reachable with S/N~10 in 10^4 sec.
SQ13: How do circumstellar disks evolve and form planetary systems?	Measure the structure, lifetime, and composition of gas in circumstellar disks.	UV spectra of protoplanetary circumstellar disks, including 912-1150A to study H_2. Velocity resolution as high as 3 km/s for kinematics. Sensitivity ~10^{-17} erg/cm^2/s/A in 3 hours to study line profiles. Requirements a bit relaxed for mass determination to study evolution. Study composition of extrasolar planetesimals with UV spectroscopy of secondary gas in debris disks. Absorption from wide range of species (1000 – 2800 A) at ~ 1 km/s resolution. Spatially resolved resonantly scattered gas emission requires long-slit spectroscopy. Study spatial variation of composition of protoplanetary disks – particularly the dusty material - in the nearest star forming regions through observations of solid state and molecular features. Image protoplanetary disks searching for discontinuities associated with the ice line or gaps produced by forming planets.	

Comments:

Aki Roberge: ALMA will contribute greatly to the study of circumstellar disk formation and evolution, especially with respect to the dust and CO spatial distributions. But ALMA can't do H_2 or ~300 K water. That being said, I'm afraid this portion on disks isn't sufficiently focused. The science requirements statement above is rather sweeping and we certainly can't do it all with this facility. I think we need a theme and also to consider what ground JWST will cover in this area.